Determining the Characteristics and Mechanisms for Biological Clutter and Environmental Reverberation and their Impact on Long Range Sonar Performance in Range-Dependent Fluctuating Ocean Waveguides

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LONG-TERM GOALS AND OBJECTIVES

Determine the temporal and spatial characteristics, and physical mechanisms for clutter and environmental reverberation in instantaneous-wide-area underwater acoustic imaging and surveillance systems. This understanding is used to develop operational and signal processing techniques to distinguish clutter from scattered returns due to man-man targets, and to determine the limits placed by environmental reverberation on target detection. In the second area, the statistical properties of broadband acoustic signals transmitted and scattered in range-dependent ocean waveguides is examined. This knowledge is then used to determine the extent to which environmental variabilities limit our ability to perform target localization and parameter estimation through beamforming and matched-filtering broadband data from imaging systems in fluctuating and dispersive ocean waveguides.

APPROACH

The research effort involves developing and enhancing physics-based theoretical models for coherent and incoherent scattering from groups of fish and other biological organisms, multi-static scattering from extended targets, and environmental reverberation in *range-dependent* ocean waveguides. The vast amounts of data collected during the ONR-sponsored experiments in the Gulf of Maine in 2006 and on the New Jersey Strataform in 2003 with instantaneous-wide-area ocean acoustic waveguide remote sensing systems (OAWRS) are processed and analyzed.

WORK COMPLETED AND RESULTS

1. Analysis of Data from 2006 OAWRS Experiment in the Gulf of Maine

During the ONR-Sloan Foundation sponsored acoustic experiment in the Gulf of Maine from Sep 22 to Oct 5, 2006, both massive shoals and small discrete schools of fish were imaged daily near Georges Bank with the OAWRS system. The OAWRS source array transmitted LFM signals simultaneously with 50 Hz bandwidths at multiple frequencies from 300 to 1500 Hz making it an extremely useful data set to examine scattering from fish as a function of OAWRS operating frequency near and below their swimbladder resonance. Concurrent measurements were made using conventional fish-finding sonars (CFFS), the Simrad EK60 (38 kHz) echosounder and the Reson 7125 (400 kHz) multibeam sonar for independent confirmation of fish presence within the local water depth. Trawl surveys

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14. ABSTRACT
Determine the temporal and spatial characteristics, and physical mechanisms for clutter and environmental reverberation in instantaneous-wide-area underwater acoustic imaging and surveillance systems. This understanding is used to develop operational and signal processing techniques to distinguish clutter from scattered returns due to man-man targets, and to determine the limits placed by environmental reverberation on target detection. In the second area, the statistical properties of broadband acoustic signals transmitted and scattered in range-dependent ocean waveguides is examined. This knowledge is then used to determine the extent to which environmental variabilities limit our ability to perform target localization and parameter estimation through beamforming and matched-filtering broadband data from imaging systems in fluctuating and dispersive ocean waveguides.

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conducted during the experiment identified Atlantic herring as the dominant species present in the shoaling populations.

- *Estimating low frequency target strength of fish by correlating OAWRS and Echosounder Data*

The low frequency OAWRS and 38 kHz echosounder data (CFFS) throughout the course of the experiment have now been analyzed to determine the target strength of the shoaling population as a function of OAWRS imaging frequency. Regions with contiguous fish distributions in both systems extending several hundred meters to a few kilometers were used in the analysis. High spatial-temporal correlation was found between fish aggregations imaged with OAWRS and along line-transect measurements of CFFS. The OAWRS raw scattered intensity data were corrected for source level, two-way transmission losses and the range- and azimuth dependent resolution footprint of the receiving array to provide estimates of scattering strength (SS) in the OAWRS imagery. The inversion procedure takes into account expected incident intensity as a function of fish depth due to refraction from non-uniform water-column sound speed profile, as well as range-dependent bathymetric variations. For each segment, we calibrate for the mean target strength (TS) of individual herring at OAWRS operating frequencies by correlating the expected OAWRS SS levels from several tens to hundreds of OAWRS images with several thousand sample points of areal fish population density estimates from CFFS along the line-transect. A novel approach that we previously developed for accurately estimating the frequency dependence in scattering from fish groups by differencing OAWRS images acquired simultaneously at multiple frequency bandwidths is also applied in the analysis.

The experimentally determined mean TS for various shoal segments drawn from more than 7 consecutive days of OAWRS measurement are found to be consistent. The measured TS increases significantly, as much as 20 dB, as the probing frequency increased from 400 Hz to 1200 Hz. The background reverberation increased only slightly, by about 4 dB making fish clutter from herring much more significant above 1 kHz. The TS are found to be consistent with scattering from an air-filled swimbladder at sub-resonance frequencies.

The TS dependence of fish differs from that of underwater vehicles. In the resonance frequency range of most fish species, roughly several hundred Hz to a few kHz, fish scattering varies significantly by more than 20 dB at resonance and off resonance frequencies. In contrast, scattering from underwater vehicles remains fairly consistent, varying monotonically by a few dB across the same band. *This experiment shows that a multi-frequency sonar system can be very effective at distinguishing fish returns from man-made targets.*

- *Classifying fish species and distinguishing fish returns from man-made objects.*

Many species of oceanic fish band together in large shoals that can span tens of kilometers and involve hundreds of millions of individuals. Grouping leads to survival advantages through enhanced spawning, predator avoidance, and feeding mechanisms. Little information has been available about the formation process and behavior of large oceanic fish shoals. Traditional methods rely on local measurements from slow-moving research vessels that enable sampling of only a small fraction of a shoal during an entire survey, typically by vertical profiling, and cannot distinguish between temporal and spatial changes. Using OAWRS images of the shoaling Atlantic herring populations in the Gulf of Maine, we describe fundamental temporal and spatial processes by which vast oceanic shoals form by observation of entire shoals in space and time over their full horizontal extent and relate these processes to likely governing mechanisms. We show that (i) a rapid transition from disordered to

highly synchronized behavior occurs as population density reaches a critical value; (ii) organized group migration occurs after this transition; and (iii) small sets of leaders significantly influence the actions of much larger groups. Each of these findings confirms general theoretical predictions believed to apply in nature irrespective of animal species. An understanding of the temporal-spatial behaviour of fish groups can be used to derive operational cues to distinguish biological clutter from returns due to man-made targets.

2. Development of a theoretical model for the multiply scattered, matched filtered field moments from a random distribution of discrete scatterers in a range-dependent fluctuating dispersive ocean waveguide

A numerical Monte-Carlo model is being developed to determine the statistical moments of the scattered returns from a randomized distribution of discrete scatterers after matched filtering in a random ocean waveguide. The model will be applied to examine numerous issues when inferring the areal population densities, spatial distributions, and mean target strengths of fish populations from their matched filtered scattered intensities measured from long ranges with OAWRS. The effects of (1) multiple scattering, (2) attenuation due to scattering, and (3) modal dispersion on fish population density imaging will be investigated. The model uses the parabolic equation to simulate acoustic field propagation in range dependent fluctuating ocean waveguides. The conditions for when multiple scattering is significant will be determined as a function of the fish volumetric density, depth extent, and target strength which depends on the imaging frequency. Attenuation due to scattering is accounted for by implementing a complex scatter function for each individual. Attenuation can negate the effects of multiple scattering but is dependent on swimbladder resonance damping for fish. The model can also determine the optimal sound speed for charting scattered returns in range in a random ocean waveguide with depth-dependent sound speed profile. Results of the model will be applied to interpret OAWRS imagery of shoaling Atlantic herring populations acquired during the 2006 Gulf of Maine Experiment. The model can also be applied to analyze scattered fields from other groups of discrete scatterers, such as bubble clouds and swarms of AUVs.

3. Develop scattering model for vertically extended targets in range-dependent waveguides

In real ocean waveguides, the water column sound speed profile can vary significantly as a function of depth leading to acoustic field propagation that is highly refractive. We have shown that the effect of non-planar incident field on the scattered field from finite vertically extended targets must be accounted for. To quantify the effects, a theoretical model for the scattered field from a vertically extended cylindrical target that accounts for non-planar incident field over the target depth by direct application of Green's theorem has been developed. The locally scattered field on the target surface at each depth is estimated as a function of the incident field by applying the boundary conditions on continuity of acoustic pressure and normal velocity, making the model applicable to general penetrable cylinders. Since the scattering contributions are calculated at each depth of the target, the object does not need to be located in an iso-speed layer. Furthermore, the scattering model for vertically extended cylindrical targets developed here can be implemented using both normal modes and the parabolic equation (PE) acoustic propagation models making the approach applicable to general range-dependent environments.

The formulation is applied to calculate the scattered field from the cylindrical BBN target in several shallow water environments with different sound speed profile and bathymetry. The BBN target is

often deployed during acoustic experiments serving as a passive acoustic reflector for its known high target strength. Experiments that have deployed the BBN target include the ONR-sponsored 2006 OAWRS Experiment at Georges Bank in the Gulf of Maine, and the 2003 Acoustic Clutter Imaging Experiment in the New Jersey Strataform under the ONR Geoclutter Program. The BBN target is essentially a 30 m long and 7 cm diameter air-filled cylindrical hose made of gum rubber, suspended vertically off the seafloor at specified depths using a combination of anchors and floats. It provides a means to validate full-field waveguide scattering models and to minimize charting errors in range and bearing for active sonar systems. The scattered field from the BBN targets can also be compared to that from other targets of interest, such as fish schools, underwater vehicles, and the sea bottom, in order to determine their relative target or scattering strengths.

The scattering of sound by an object in an ocean waveguide is complicated due to multi-modal propagation and dispersion. The ocean-acoustic standard, Ingenito waveguide target scattering model, is a widely used method to calculate the single scattering from arbitrary sized objects in a horizontally stratified ocean waveguide. This approach is based on normal mode theory and it decomposes the incident field at the target center into modal plane waves. The object's plane wave scatter function is used to couple the incident and scattered modes which are then propagated to the receiver. The Ingenito model is therefore valid for large scatterers, large compared to the acoustic wavelength, in an ocean waveguide. However, it only applies to objects contained within an iso-speed layer because of modal plane wave decomposition at the target center. The Ingenito model cannot account for changes in medium sound speed along the target depth and assumes that the incident field is planar over the target extent.

The theoretical vertically extended cylindrical (VEC) target waveguide scattering model is first calibrated against the Ingenito model for the BBN target in a Pekeris waveguide where the target is contained within the iso-speed water column layer. The two models lead to scattered field levels as a function of range that match perfectly in this environment. The VEC model is then implemented in a waveguide with the highly refractive water-column sound speed profile from the Gulf of Maine. In this environment, the BBN target extends over a depth where the water-column sound speed cannot be approximated as a constant and the field incident on the target is highly nonplanar. We show that when the Ingenito model is applied in this environment, it leads to significant errors of 10 dB or more in estimating the scattered field level for the BBN target.

We are now validating the scattering model for vertically extended cylindrical (VEC) targets in range-dependent ocean waveguides with experimental data from the 2006 OAWRS experiment in the Gulf of Maine. In order to take into account the scintillation in the measured scattered intensity caused by spatial and temporal fluctuations of the ocean waveguide, a stochastic approach is adopted. Monte Carlo simulations of the scattered field statistics are calculated by implementing the VEC model in a range-dependent environment randomized by internal waves. The simulated scattered field statistics for different source-receiver-target configurations is compared to the scattered returns from BBN targets measured during the 2006 Gulf of Maine experiment. Preliminary analysis show good agreement between the simulated and experimental scattered field statistics from the BBN target.

IMPACT/APPLICATIONS

We have determined the dominant physical mechanism by which fish schools cause clutter in Navy sonar systems as scattering arising from their air-filled swim bladders. We also verified with data that the frequency dependence in scattering from fish swimbladder is well modeled as a resonant spheroidal

bubble. Furthermore, a multi-frequency Navy sonar system that spans from several hundred Hz to a few kHz will be very effective in distinguishing fish clutter from underwater vehicles.

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